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Interaction of the Quasi Two-Day Wave with other Planetary Waves in the Middle Atmosphere

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Zusammenfassung
Die nichtlineare Wechselwirkung der Quasi Zwei-Tage Welle (QZTW) mit anderen planetaren Wellen führt zu wesentlichen Amplitudenmodulationen der Zwei-Tage Welle und zu einer Reihe auftretender sekundärer Wellen. Die Ergebnisse der verschiedenen Experimente zur Wechselwirkung der Quasi Zwei-Tage Welle mit jeweils der 10-Tage Welle, der 16-Tage Welle und der 5-Tage Welle zeigen, dass die Amplitude der QZTW unter der Wechselwirkung mit der 16-Tage Welle und der 10-Tage Welle um bis zu 20% reduziert wird. Die stationäre planetare Welle mit der zonalen Wellenzahl 1 (SPW1) scheint die wichtigste Rolle bei den nichtlinearen Wechselwirkungen mit der QZTW zu spielen, da die daraus entstehenden sekundären Wellen mit den Wellenzahlen 2 und 4 dieselbe Periode wie die QZTW haben. Die Überlagerung der Quasi Zwei-Tage Welle und ihrer sekundären Wellen verstärkt die Amplitude um bis zu 60%.

Summary
The non – linear interaction of the quasi two-day Wave (QTDW) with other planetary waves leads to remarkable amplitude modulations of the QTDW and to arising secondary waves. Results of several numerical experiments considering the behaviour of the QTDW in connection with the 16-, 10-, and 5-day wave have shown that the amplitude of the QTDW reduces under interaction with the 16DW and 10DW. The stationary planetary wave with zonal wave number 1 (SPW1) seems to play the most important role, because resulting secondary waves exhibit the same period as the QTDW. The superposition of these waves leads to an enhancement of the QTDW-amplitude up to 60%. This means, that a strong amplification of the QTDW measured by RADAR instruments can be due to interaction between the QTDW and a strong SPW1.

1 Introduction

The quasi two-day wave (QTDW) is a striking feature of the summer middle atmosphere. It appears very regulary in one or two bursts shortly after solstice in the summer middle atmosphere. The observed properties of the wave do not give a unique picture that links to one well – defined mechanism. The wave appears with the zonal wave number 3 as well as with wave number 4. The period lies between 45-53 hours. This phenomenon can be observed in both hemispheres but with differences in period and strength of amplitudes which are stronger in the southern hemisphere than in the northern hemisphere. Meridional wind amplitudes v' were found up to $20\,m\,s^{-1}$ (Gurubaran et al., 2001) in the northern tropics as well as at 52°N (Jacobi et al., 1997), while Craig and Elford (1981) and Plumb et al. (1987) reported speeds of between $40-50\,m\,s^{-1}$ for Australia. Satellite observations during January 1992 (Wu et al., 1993) gave up to $60\,m\,s^{-1}$ for v' at the equator, while the zonal component was observed with $30\,m\,s^{-1}$ at low to middle latitudes in the southern hemisphere. Thus, the wave's behaviour raises the question about its origin.

From the theoretical point of view, the QTDW can be derived as a solution of the Laplace' tidal equations. It is then referred to the Rossby-gravity mode (3,0). However, according to this solution the wave should be a permanent feature of the middle atmosphere. Thus, this theory cannot explain the sudden onset and offset of the wave during summer. Besides, several studies have shown, that a QTDW might develope as a result of an unstable jet in the summer mesosphere. On the other hand, the knowledge about the interactions of the QTDW with other disturbances in the middle atmosphere is still sparse but these interaction might play an important role on the amplification of the QTDW.

The mechanistic model COMMA-LIM (Cologne Model of the Middle Atmosphere – Leipzig Institute for Meteorology) was used to study the wave, its propagation and impact on the mean flow by forcing it as an Eigenmode of the atmosphere. This paper presents the results of investigation on the interactions of the QTDW with other planetary waves. For a detailed description of the model the reader is kindly referred to Fröhlich et al. (2003).

1.1 Experimental setup

For the numerical investigations the month of July was chosen. Therefore the model was established for the 1th of July as a starting point for all experiments. Then the calculations were made for the whole month and the analyses represent the climatological values of July.

The quasi two-day wave was inserted into the model as a heating disturbance per unit mass at around the tropopause level. The forcing itself was smoothed in the vertical with an exponential factor F and the disturbance term h_{2dw} was defined by the properties of the wave:

$$h_{2dw} = A\,\Phi(\phi)\,F(z)\,cos(k\,x - \omega\,t) \tag{1}$$

where $F(z) = exp[-\frac{(z-10)^2}{25}]$ with z in km, A is the amplitude scaled to produce the observed values, $\Phi(\phi)$ represents the latitudinal structure of the wave, obtained from Hough-mode calculations for the Rossby-gravity wave (3,0) (Swarztrauber and Kasahara, 1985). The zonal wave number is given by $k = 3$, $x = 2\pi\lambda/360°$. Within the angular frequency $\omega = 2\pi/T$ the period $T = 52.5\,h$ has been chosen, as this period gives the resonant response in COMMA-LIM.

In Fig.(1) the amplitudes of the QTDW in the wind, temperature and geopotential fields are displayed. The main characteristic is the maximum of the meridional wind above the

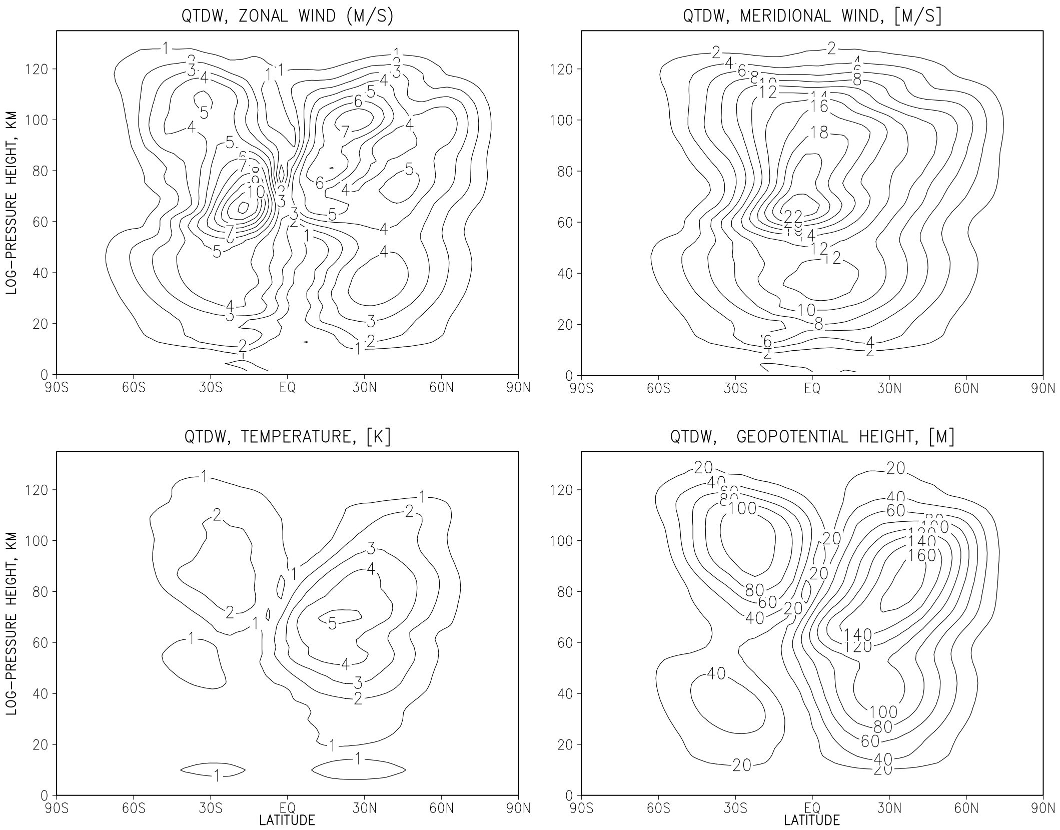

Figure 1: Amplitudes of the QTDW with wave number 3, and period $T = 52.5\,h$ for zonal and meridional wind, temperature and geopotential.

equator while the other variables show maxima in both hemispheres – more pronounced in the summer hemisphere – and a node at the equator. The meridional amplitude shows a maximum in the equatorial mesosphere which is twice as strong as that for the zonal wind. With increasing latitude towards the north pole both wind components become comparable in magnitude. All amplitude fields show a well – pronounced propagation into the summer hemisphere and a suppression of the wave on the winter side. However, the amplitudes of the QTDW as obtained with COMMA-LIM do not show a transient behaviour during the course of July. This is consistent with the theory of Eigenmodes but not with observations. Therefore, additional investigations are necessary to clearify if the assumption of the QTDW as an Eigenmode is wrong or if there mechanisms exist that modulate the Eigenmode – amplitude on a relatively short time-scale of several days.

2 Interaction between planetary waves

The theory of a non – linear coupling between two planetary waves or a planetary wave and tides says that two "primary" waves can interact through the advection terms in the momentum equation and produce a family of "secondary" waves (Teitelbaum and Vial, 1991). For instance, if a signal consisting of two cosine waves with zonal wave numbers and frequencies (k_1, σ_1) and (k_2, σ_2) pass through a quadratic system, the output of this system

Listing	Experiment
A	run with steady forced QTDW and SPW1
B	run with steady forced QTDW and 16DW
C	run with steady forced QTDW and 10DW
D	run with steady forced QTDW and 5DW
E	run with steady forced QTDW but without SPW1

Table 1: Overview of the experiments.

will contain the secondary waves $(2k_1, 2\sigma_1)$,$(2k_2, 2\sigma_2)$, $(k_1 + k_2, \sigma_1 + \sigma_2)$, $(k_1 - k_2, \sigma_1 - \sigma_2)$. The strongest secondary waves are those whose frequencies are the sum and difference of the frequencies of the primary waves. The secondary waves then beat with the primary waves and modulate the amplitude of the higher – frequency wave at the period of the lower – frequency wave.
Since the QTDW was observed in most cases as a burst with a length of between two weeks and one month, Jacobi et al. (1998) analysed the 14-year data set of summer Collm-winds with respect to correlations between the 2-day wave and other planetary waves. For some cases non – linear interaction was found to be responsible. Expected secondary waves resulting from non – linear interaction with the 16-day wave (16DW) and 10-day wave (10DW) were found as well. However, the correlation between the secondary waves and 16-day wave was rather weak and could not be the only process responsible for periodic variations of the QTDW. In some years the wave was found to be divided into two frequencies, which could result from self-interaction of the QTDW during its appearance.
Pancheva et al. (2000) reported on possible non – linear interactions of the QTDW with the 10DW, 16DW and tides for the years 1992 and 1993. Interaction between the QTDW and 10DW was found to appear in both summers, whereas a strong signal of interaction with the 16DW only occurred in 1992. Nevertheless, the QTDW was involved in many planetary – wave interactions during summer and the splitting up into periods of 1.7 and 2.1 days was assumed to be related to this phenomenon.

2.1 COMMA-LIM results

In table(1) the different experiments are listed which investigate the interaction between the QTDW and other planetary waves, such as the stationary plantetary wave with zonal wave number 1, the 16-, 10-, and 5-day wave (SPW1, 16DW, 10DW, 5DW). Table (2) lists the main secondary waves arising from interaction of the QTDW with the subsequent PWs. Wave analysis was made using the method of least squares. Together with the estimated periods the results from a power spectrum using a fast Fourier Transformation are listed. It was found, that secondary PW signals arising from interaction with the 16DW and 5DW are either small or not detected. This result was confirmed when the amplitudes of possible secondary waves were calculated.

The listed secondary waves arising from the sum and the difference of the primary waves are plotted in Figs.(2) and (3). The strongest response resulted from the interaction between the QTDW and SPW1 and the waves arising from QTDW/10DW interaction. Wave number 2 shows always stronger signals than wave number 4. The secondary $k = 2$

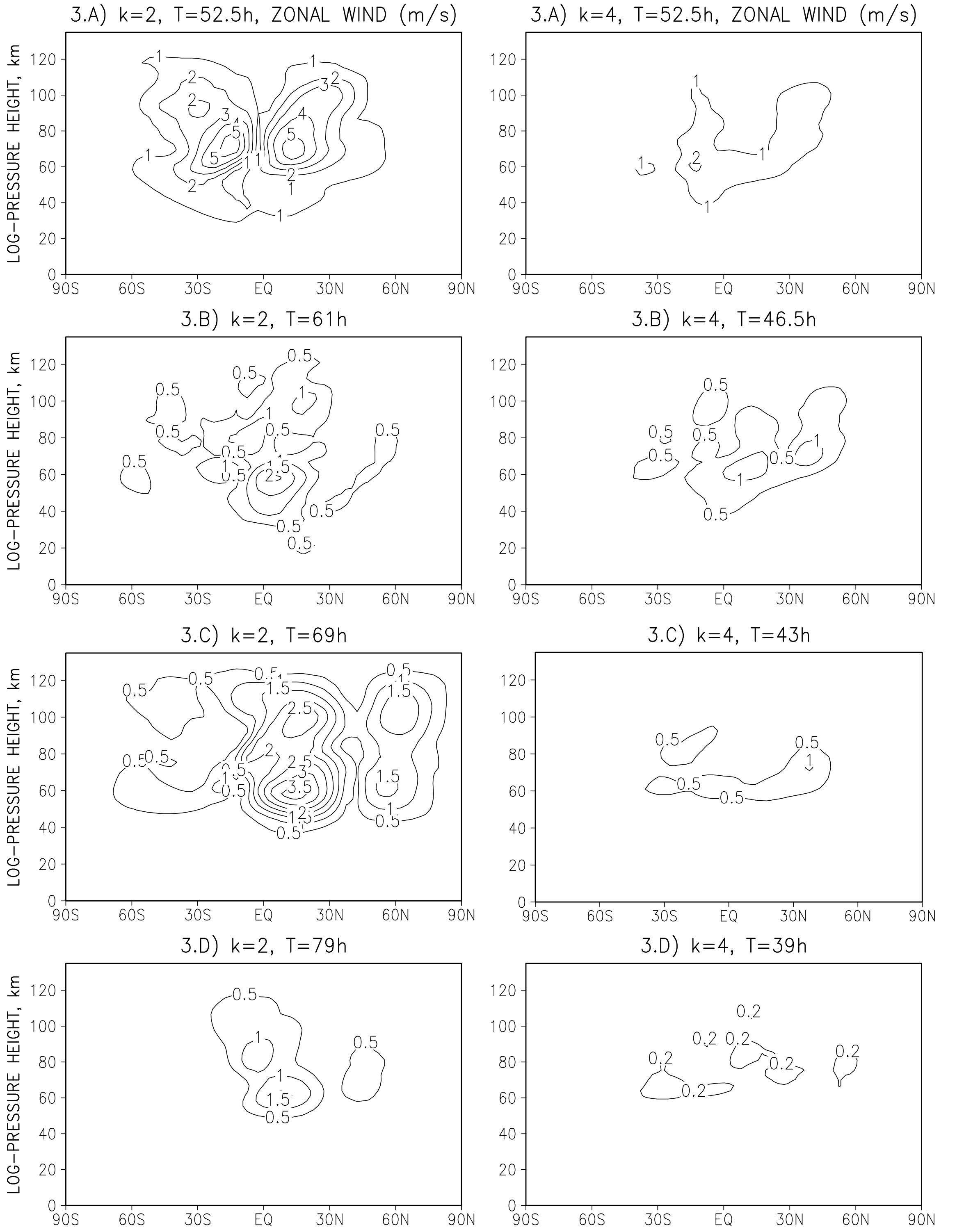

Figure 2: Zonal wind amplitudes of secondary planetary waves due to interaction of different planetary waves and QTDW. Left panels represent waves with $k = 2$: A) QTDW-SPW1, B) QTDW-16DW, C) QTDW-10DW, D) QTDW-5DW. Right panels show waves with $k = 4$: A) QTDW+SPW1, B) QTDW+16DW, C) QTDW+10DW, D) QTDW+5DW.

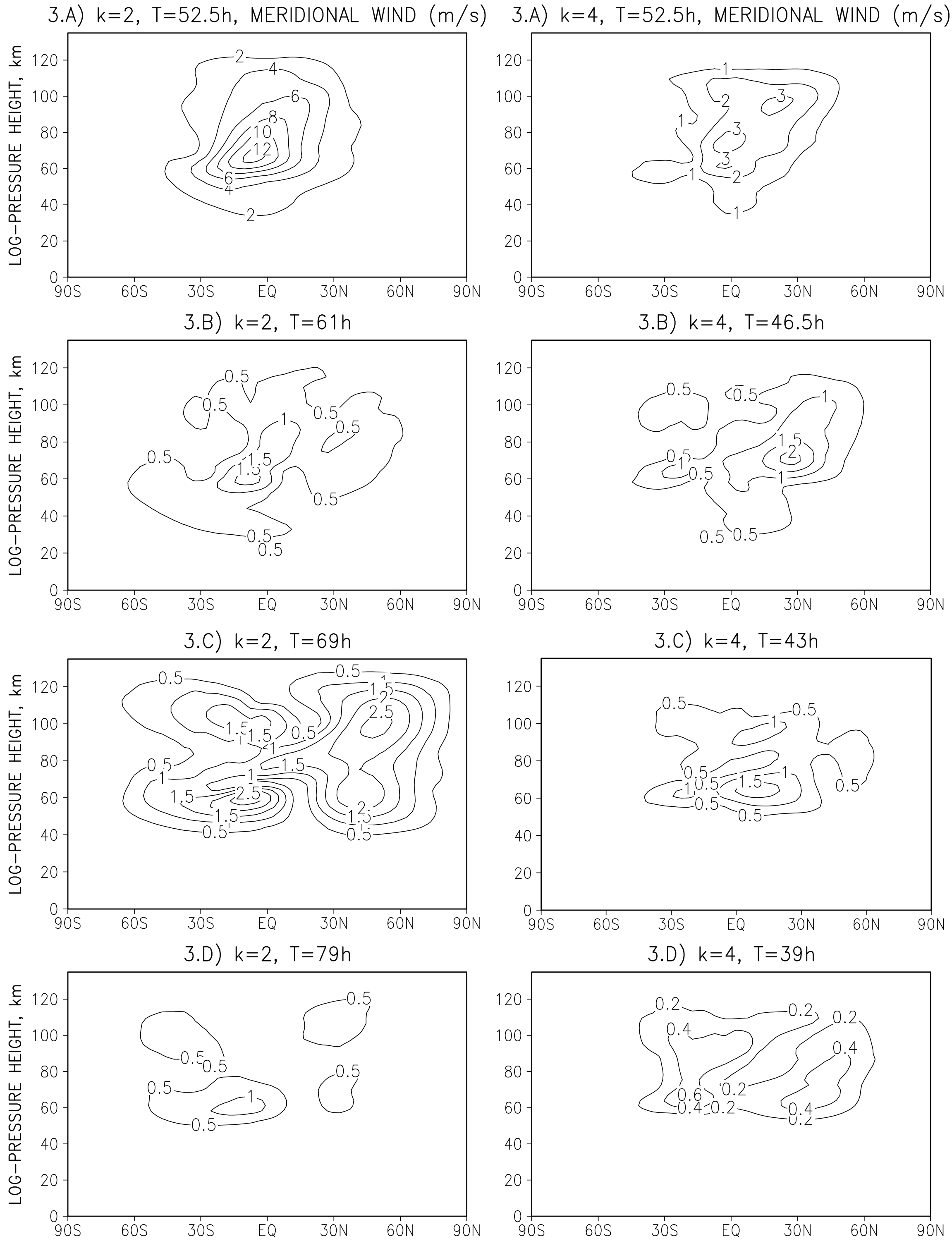

Figure 3: As in Fig.(2) but for meridional wind amplitudes.

Interaction	**Wave number of secondary PW** ($k_{sPW} = k_1 \pm k_2$)	**Period of secondary PW (h)** ($1/T_{sPW} = 1/T_1 \pm 1/T_2$)	**Spectral analysis (h)**
$QTDW$+SPW1	4	−52.5	51.2
$QTDW$−SPW1	2	−52.5	53.9
$QTDW$+16DW	4	−45	46.5
$QTDW$−16DW	2	−61	−
$QTDW$+10DW	4	−42.3	42.6
$QTDW$−10DW	2	−69	68
$QTDW$+5DW	4	−39.3	39.4
$QTDW$−5DW	2	−79	−

Table 2: Secondary waves arising from the sum and the difference of the primary waves. The negative or positive sign at the period corresponds to westward or eastward propagating waves, respectively.

wave resembles the shape of the QTDW, and also shows stronger amplitudes for the meridional wind than for the zonal wind. For all other waves both wind fields have the same order of magnitude.

Modulation of QTDW by 16DW and 10DW

Fig.(4) shows a time – height plot for two different latitudes which depicts the modulation of the QTDW by the two large planetary waves. This picture is obtained by drawing the difference of the 'undisturbed' QTDW amplitude in experiment A from the two amplitudes of the QTDW calculated in experiments B and C.
The variation in the zonal wind field at 32° N (not shown here) accounts for $1.5\,m\,s^{-1}$ representing an ∼ 20% change, whereas the meridional component is modulated strongest at the equator with around $4\,m\,s^{-1}$ (referring to an 8% change). By comparing the behaviour at different latitudes it can be seen the strength of modulation decreases towards higher latitudes at mesospheric heights. Furthermore, increasing modulation in the course of July can be seen. Thus, these are mechanisms that could be responsible for transient – like behaviour of the QTDW if not for burst – like events. However, COMMA-LIM results showed a weaker modulation than that reported by Pancheva et al. (2000). In their study the variation of wave amplitudes exceeded 400% between minimum and maximum. Additionally, in observations by Pancheva et al. (2000) the QTDW seemed to grow through the interaction with the 16DW, whereas in COMMA-LIM the 16DW-modulation results in smaller amplitude values than those for the controlled QTDW (positive differences between control and modulated QTDW). Similar results are obtained for the modulation of the QTDW by the 10DW. The modulation begins also at around $60\,km$ height (where the winter planetary waves penetrate into the summer hemisphere) and is comparable in magnitude and latitudinal decrease of modulation.

Interaction of QTDW and SPW1

Strong secondary waves arised from interaction of these two waves (experiment A) as

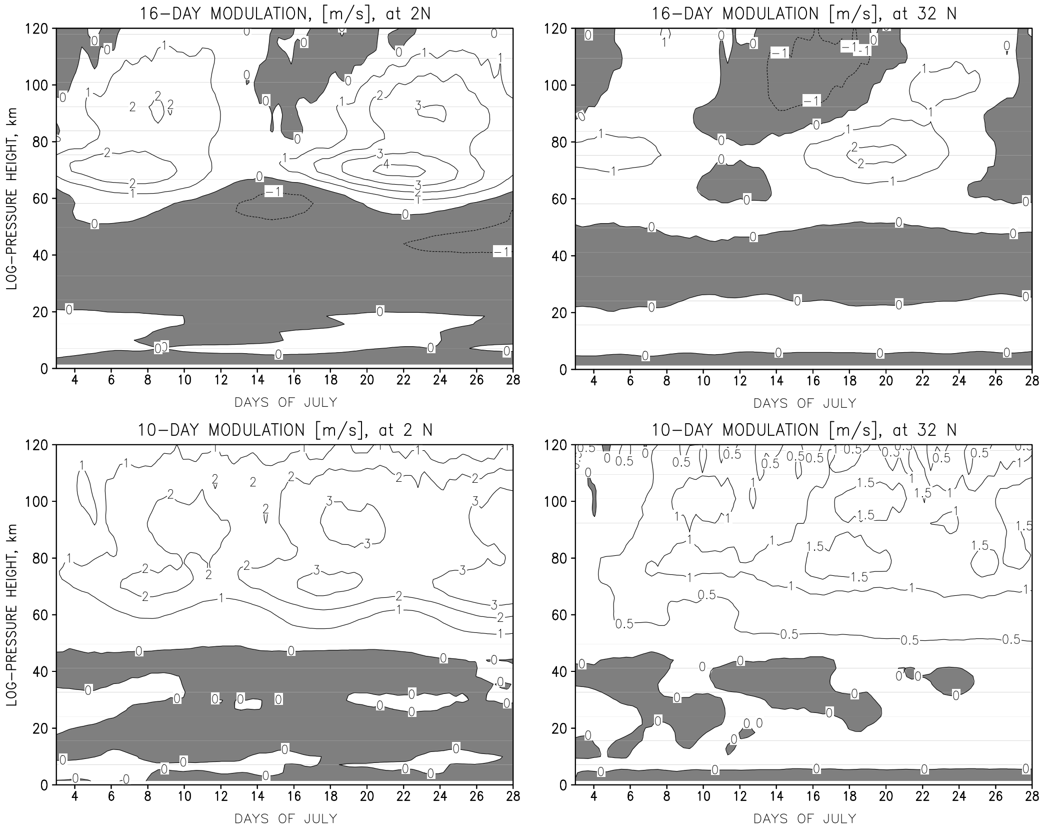

Figure 4: Top panels: time-height plot of modulation of the QTDW by the 16DW. Bottom panels: Modulation by the 10DW. Amplitudes of meridional wind are displayed near the equator (left) and mid-latitudes.

shown in the top panels of Figs.(2) and (3). Especially the wind amplitudes of wave number 2 show values that reach of about 50 % of the original QTDW, and the structure looks similar to the primary QTDW. It was proved if the $k = 2$ QTDW arises from interaction with the stationary planetary wave and not as a sub harmonic of the diurnal tide by carrying out a separate calculation without the SPW1 (experiment E). Then, such waves did not arise. Furthermore, the very weak response of the self-interacting diurnal tide propagates in an absolut different way in the middle atmosphere the $k = 2$-QTDW does. Wave number 4 is not as strong but still more pronounced than other secondary PWs. A further interesting feature of experiment E is that the QTDW forced without the presence of a SPW1 exhibits amplitudes of the same magnitude as in case A. It means that the energy flux from the non – linear interaction of the primary waves that feeds the secondary waves is dominantly provided by the SPW1. Under this assumption transient events of SPW1 will increase the secondary wave amplitudes. The secondary QTDWs indicate that it seems necessary to take them into account when comparing the QTDW with radar measurements. Local measurements are only able to collect the frequency but cannot account for different wave numbers of the observed oscillations or divide them into parts of primary and secondary waves.

By restoring the three waves back to the longitudinal grid the superposition of the waves with equal frequency but different wave number and amplitude shows a wave with

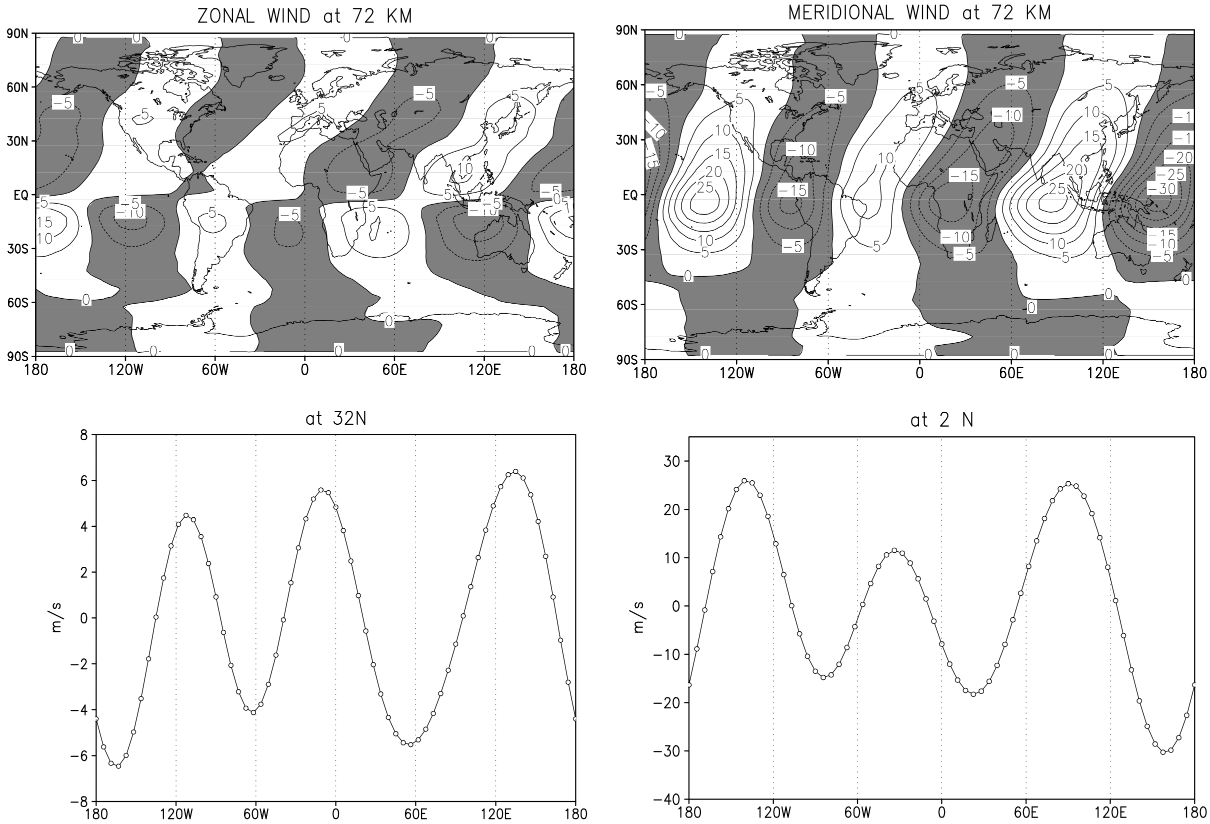

Figure 5: Superposition of wave numbers 2, 3 and 4 with period of $52.5\,h$ for zonal (left) and meridional (right) wind. Upper panels show a longitude-latitude section at $72\,km$, whereas lower panels depict the sum at a specific latitude.

the wave number of the strongest amplitude, see Fig.(5). The longitude-latitude plots at a height of $72\ km$ show that the wave number changes from 3 to 2 in the high-latitude winter hemisphere; however, there the QTDW amplitudes are smaller than $5\,m\,s^{-1}$. Nevertheless, regarding this picture it seems possible that the wave number can change at specific latitudes or altitudes if one of the secondary waves grows stronger than the primary QTDW. The characteristic feature of the not equally distributed distance between two ridges over the latitudinal circle develops due to beating between the three waves. In the bottom panels of Fig.(5) a clear example is given for the wind amplitudes at $32°\,N, 72\,km$ height. Wave number estimation from radar stations at different longitudes would yield in this case a non – integer wave number as was the case in the papers by Poole and Harris (1995) and Meek et al. (1996). The authors of these papers suggested that beating of waves might be responsible for wave number ambiguities. COMMA-LIM model investigations could confirm this assumption and explain it by taking into account the SPW1-QTDW interaction. The sum of the 2-day waves (wave number 2 to 4) with the same period $52.5\,h$ gives an increase of amplitude of about 60% (not shown here) in zonal and meridional wind when compared with the wave number-3 part alone.

3 Conclusions

To summarise, the interaction of the QTDW with other PWs leads to significant amplitude modulations of the quasi two-day wave and a number of secondary PWs arise. The SPW1 seems to play the most important role in these non – linear interactions since the developing secondary PWs have the same period as the primary QTDW. Thus, radar data from a single station that cannot distinguish between the wave numbers may observe increased QTDW amplitudes at a time, where the SPW1 shows a transient behaviour.

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